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Entrained flow gasification of torrefied wood residues

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Abstract

In this work, four different fuels were gasified in a pressurized entrained flow pilot plant gasifier at approximately 270 kW_{th}. The different fuels were; two torrefied wood residues, one raw wood residue and one torrefied stem wood. The system pressure and oxygen equivalence ratio (λ) were held constant for all four gasification experiments. It was found that the torrefaction pretreatment significantly reduced the milling energy consumption for fuel size reduction, which in turn contributed to increased gasification plant efficiency. Furthermore, the results indicate that the carbon conversion efficiency may be enhanced by an intermediate torrefaction pretreatment, whereas both less- and more severe torrefaction resulted in reduced carbon conversions. The results also indicate that the CH₄ yield was significantly reduced for the most severely torrefied fuel.

Highlights

- The torrefaction pretreatment reduced the milling energy consumption.
- Torrefaction pretreatment contributed to increased gasification plant efficiency.
- The fuel carbon conversion efficiency was affected by torrefaction pretreatment.
- The CH₄ yield from gasification was reduced for severely torrefied fuel.

Keywords

Entrained-flow gasification, Biomass, Torrefaction, Wood, Syngas, Methane

1 Introduction

Large-scale, pressurized entrained flow gasification (PEFG) of fossil coal has proven industrially preferable in terms of cost-efficiently producing a clean product gas, essentially free from products of incomplete gasification such as char, soot, tars and other lower molecular weight hydrocarbons (e.g. CH₄, C₂H₂) [1]. This high conversion efficiency as well as the inherent fuel flexibility are two major advantages of the PEFG-process. There are enough coal based installations around the world, 96 (2010), demonstrating the economic viability of the PEFG process [2]. Global coal based installations are consequently continuously increasing with the majority of the present PEFG projects generally aimed for either power production, petrochemicals or liquid fuels production in China and US [2].

A number of studies have also identified PEFG as one of the most promising technologies for large-scale biomass conversion to higher-value energy carriers, liquid fuels and petrochemicals, e.g. [3-5]. Quite few practical PEFG test campaigns have however so far been performed for biomass raw materials at pilot- or commercial scale. Pilot scale PEFG experiments with solid biomass is to our knowledge limited to the

1 studies performed by Weiland et.al, where gasification of stem wood and bark mixtures
2 were gasified at approximately 200 kW scale [6, 7]. In addition to this, Wolters et al.
3 and Padban described occasional trials of co-firing coal and biomass in a 250 MW_e
4 IGCC plant in Buggenum [8, 9]. In the study of Padban, torrefied biomass corresponded
5 to approximately 70% of the fuel mixture on energy basis. One reason for this limited
6 experience is that biomass powder is generally considered difficult and problematic in
7 terms of feeding [10, 11] and ash behavior [5, 12].

8 Compared to fossil coal powder, the use of powder from traditional biomass materials
9 may result in increased tar formation and methane production due to lower flame
10 temperature primarily because of the lower heating value of the biomass. Furthermore,
11 production of powder from traditional biomass often needs expensive equipment
12 adoptions or reconstruction of existing coal handling and powder production equipment.
13 Some kind of biomass pretreatment would therefore be desirable to facilitate the use of
14 commercially available, lower cost and proven handling equipment either in the coal
15 PEFG-train with no or minor adaptations, or in new biomass based installations.

16 Torrefaction has been identified as such a (promising) thermal pretreatment method to
17 potentially facilitate large-scale cost-efficient PEFG of biomass. By exposing the
18 biomass to temperatures in the region of 230-350°C during 1 to 60 minutes, a number of
19 critical material properties are significantly improved to the benefit of subsequent
20 conversion [13]. During the process, biomass is degraded and volatiles are released as
21 torrefaction gas, decreasing the oxygen content and increasing the carbon content of the
22 biomass material. These changes also improve the heating value and friability (i.e. also
23 powder size distribution after milling) of the biomass material, and thus potentially
24 influencing both gasification process chemistry and the efficiencies of the process.

Furthermore, the fuel particles may become more spherical, making it more easily to feed in pneumatic systems.

Because of the generally improved characteristics of torrefied and compacted biomass materials, the whole supply chain of raw material handling, storage and transportation is significantly improved; costs and carbon footprints are reduced as exemplified by for example Uslu et al. and Svanberg et al. [14, 15]. Comparing different pretreatment methods and supply systems for biomass feeding of large-scale PEFG plants it has been concluded that a feedstock based on torrefied materials to be the preferable route for introducing biomass to PEFG systems already developed and available for coal [3, 16, 17]. Another important aspect in favor for biomass pretreatment by torrefaction is the significant variations in market conditions and thereby economy of a large-scale gasification plant as a result of varying feedstock, CO₂ credit and electricity prices. Meerman et al. stressed the importance of flexible feedstock operation, i.e. industrial systems facilitating straightforward switching between coal and torrefied biomass, depending on varying economic and raw material prerequisites [18-20]. A green coal in the form of torrefied biomass materials would facilitate this flexibility since the existing coal feeding system can be used for the torrefied materials while traditional biomass requires a dedicated fuel feeding system [19].

The changes imposed on the biomass during torrefaction may however also result in reduced performance in the PEFG process as volatile matter is decreased and reactivity changed. The process chemistry and behavior of the fuel particles are significantly influenced by the volatile content, particle size distribution and morphology, where the reduced volatile content could decrease reactivity but the smaller particle sizes instead increase the conversion rate during gasification. It should however be stated that the higher reactivity of biomass may in fact allow less requirements on size reduction than

what is experienced with coal and also facilitating sufficiently high gasification efficiency at a somewhat lower temperature.

In the work by Couhert et al. [21], atmospheric steam gasification of beech wood and torrefied beech wood was studied in a lab-scale drop-tube furnace at 1200°C and 1400°C. It was found that the amounts of residual carbon (char that was not gasified by steam) were higher for the torrefied wood fuels compared to the original beech wood at 1200°C. This indicates a reduction in fuel conversion efficiency for the torrefied fuels by gasification with steam. However, Chen et al. [22] found that the torrefaction temperature affected the cold gas efficiency (CGE) of their experiments with sawdust performed at 1200°C in a drop-tube furnace using O₂ as the gasification agent. They found an optimum in CGE (i.e. also fuel conversion) at a torrefaction temperature of approximately 250°C, whereas both less- and more severe torrefaction pretreatment resulted in lower CGE. This result was attributed to the measured pore structure of the fuels, where the sawdust torrefied at 250°C had the largest specific area and smallest pore size.

Based on the experimental results from the drop-tube experiments described above, [21, 22], there is an indication that severely torrefied fuels may result in reduced carbon conversion efficiency from gasification. However, the drop-tube results were both obtained with controlled fuel particle size distributions (by sieving) under *allothermal* conditions at fixed gasification temperatures in lab-scale (<2 kW). In the present work we compare the operation of an *autothermal* pressurized entrained flow pilot-scale gasifier (approximately 270 kW) using a reference wood powder and different torrefied materials. The primary objective was to (1) study the effect of torrefaction on the fuel carbon conversion efficiency and (2) study how the syngas content of CH₄ is affected by the torrefaction pretreatment. This is an important factor if the syngas is intended for

1 catalytic conversion to synthetic motor fuels, or chemicals, since the CH_4 often is inert
2 through the synthesis plant and therefore only accounts as losses.

3 The secondary, more general, objectives of the present work was to; (3) evaluate the
4 feasibility of feeding and operating the gasifier on torrefied biomass powder and (4)
5 evaluate if the torrefaction would significantly change gasification plant performance.

6 **2 Materials and Methods**

7 ***2.1 General description of the pilot plant***

8 The Pressurized Entrained flow Biomass Gasification (PEBG) pilot plant, situated at
9 Energy Technology Centre (ETC) in Piteå, Sweden, was designed to operate in slagging
10 mode with process temperatures ranging between 1200 - 1500°C. The pilot plant is
11 described in detail by Weiland et al. [6] and therefore only a brief description is given
12 here. A schematic process flow diagram is shown in Figure 1. The PEBG gasifier
13 consist of a ceramic lined reactor followed by a bubbling 2-level water sprayed quench
14 for syngas cooling and smelt/particle separation. The process temperature inside the
15 reactor is measured by five thermocouples at different locations inside the reactor,
16 placed with the tip coincident with the inner reactor wall. One thermocouple was placed
17 at the top part of the reactor, three thermocouples in the middle part of the reactor
18 equally separated by 120° and one thermocouple in the bottom part of the reactor.

19 The fuel powders were prepared by milling the considered fuel materials in a hammer
20 mill. After milling, the fuel powders were pneumatically transported to two fuel hoppers
21 in the feeding system located above the reactor in the PEBG plant. The two hoppers are
22 operated alternately in order to sustain the process operating pressure. After
23 pressurization of the fuel hoppers, the fuel was transported by the fuel feeding system
24 and introduced in the top of the reactor. The supplied amount of O_2 used in the

gasification process was controlled by a mass flow controller (MFC) and introduced in the top of the reactor via an O₂ register located concentrically outside the fuel entrance of the burner. Moreover, the O₂ concentration in the burner O₂ register could be altered by introducing N₂ (via a N₂ MFC) into the O₂ flow. An O₂ concentration of approximately 90 mol% was used in the burner O₂ register for the campaigns described in this work.

A vertically installed electrical heater was used to heat up the reactor ceramics to approximately 1000°C prior to process start-up. After removing the electrical heater, the powder burner was installed and the gasification process was started at atmospheric pressure by feeding the fuel powder and O₂ to the reactor. Pressurization of the plant was then accomplished by gradually closing the pressure control valve on the syngas outlet until the desired pressure was reached. A general start-up procedure was to operate the gasification process at a high oxygen equivalence ratio (λ) in order to quickly reach a process temperature above 1200°C. Here λ was defined as the ratio between the supplied O₂ and the O₂ addition at stoichiometric combustion. After reaching approximately 1200°C, the process conditions were adjusted according to plan. In the case of process shut down, the reactor was purged with N₂ to evacuate all product gases before the process was restarted.

The water sprays in the quench (Figure 1) cooled the raw syngas and other products from the reactor (i.e. gases, particulates and ash/char) to temperatures below 100°C. Separated particles in the quench (i.e. ash or possible char and soot particles) either settled at the bottom of the quench or in the sedimentation vessel downstream the quench water outlet. The process pressure was controlled by a pressure control valve on the syngas outlet pipe (see Figure 1). A slip stream of the pressure relieved and cool syngas could be sampled from the outlet syngas pipe. The produced syngas flow was

1 flared on top of the building. A N₂ purged and water cooled camera probe was installed
2 in the top of the reactor. The camera was a valuable tool for the operators to
3 qualitatively analyze the gasification flame during operation. For safe process control
4 and automation, a PLC (Programmable Logic Controller) based control system was
5 used, and relevant process values were stored in a database for post processing of the
6 results from the experiments.

7 **2.2 Biomass feedstocks and preparation**

8 Four different fuels were gasified in this work; one raw wood residue (Raw); two
9 torrefied wood residues (Torr-300 and Torr-340) and one torrefied stem wood (Torr-
10 demo). The Raw fuel had a slightly different composition compared to the original
11 biomass of the Torr-300 and Torr-340 fuels. The Raw biomass consisted of wood
12 residue chips of 45% hardwood (birch) and 55% softwood (pine), whereas the biomass
13 feed for production of Torr-300 and Torr-340 were wood residue chips consisting of
14 45% hardwood (birch) and 55% softwood (whereof 35% pine and 20% spruce),
15 according to Table 1. The Torr-300 and Torr-340 were torrefied in a continuous
16 torrefaction pilot plant, where the residence time in the torrefaction reactor was set to
17 4.5 minutes and the final torrefaction biomass surface temperatures were 300°C and
18 340°C respectively. Biomass feed for Torr-demo was a mixture of stem wood chips of
19 Pine and Norway Spruce. Torrefaction of Torr-demo was performed in a continuous
20 torrefaction demo plant located in Klintehamn, Gotland, Sweden, with a maximum
21 capacity of 1 t_{DS}/h utilizing an indirectly flue gas heated rotary drum. The residence
22 time in the reactor was approximately 45-60 minutes at a temperature of 245°C. The
23 wood residues (Raw, Torr-300 and Torr-340) were in the form of chips when fed to the
24 powder mill, whereas the Torr-demo was in the form of pellets. Moisture content of the
25 powders prior to gasification was between 2 and 3%.

Torrefaction settings and fuel properties of the torrefied and the raw samples are presented in Table 1. The C, H and O composition of the Raw fuel was very close to the stem wood reference fuel described earlier by [6]. The C, H and O composition of the Torr-340 fuel showed similarities with some brown coal reference fuels described in existing literature [1, 23], whereas the Torr-300 and Torr-demo fuels were milder torrefied and approaching similar C, H and O compositions as peat [24].

The four fuels considered in this work were milled to powders using a granulator (Rapid Granulator 15 Series) and a hammermill (MAFA EU-4B) connected in series. The granulator sieve size was 5 mm, whereas the sieve size in the hammermill was 0.75 mm for all fuels. The milling power consumption was continuously logged in order to calculate the milling energy consumption for each fuel. The hammermill power consumption was measured and logged to the database with a CarloGavazzi WM22-DIN Power Analyser instrument, whereas the power consumption of the granulator was measured with a tong ammeter.

Representative samples from each fuel powder were studied in a light microscope (Zeiss Stemi 2000-C equipped with a digital camera for imaging).

2.3 Gasification experiments

The aim was to evaluate the four different fuels at similar operating conditions in the gasification process. In this work, it was decided to keep the thermal power, the system pressure and the oxygen equivalence ratio (λ) constant for the four campaigns. In Table 2 the main experimental settings for the performed gasification experiments are presented.

2.3.1 Gas sampling

Syngas sampling was performed by letting a small slip stream of the produced syngas flow from the outlet syngas pipe (after the pressure control valve) through a particulate removal equipment and a water cooled condenser. The dried syngas was then analyzed consecutively by a micro-GC (Micro Gas Chromatograph Varian 490 GC with Molecular sieve 5A and PoraPlot U columns equipped with two thermal conductivity detectors, TCD).

2.3.2 Mass and energy balances - Definitions

The total syngas flow was not measured directly. Instead, N₂ was used as a tracer making it possible to calculate the total mass flow of dry syngas from the N₂ concentration in the syngas. This is possible under the assumption that all the trace gas is inert and the added amount of N₂ ends up in the syngas, without transforming into other compounds.

The carbon conversion was calculated as the ratio of carbon atoms in the syngas (mol/s) over the amount of input carbon atoms from the corresponding fuel (mol/s) as previously described by Weiland et al. [6]. This is however different from the general definition of carbon conversion, where the definition is based on the difference between input carbon atoms from the fuel and the output carbon atoms in the gasification residue [1]. There is a potential difference between the carbon conversions calculated with these two different definitions, where the former definition (used in this work) being the most conservative.

The lower heating value (LHV) of the syngas was calculated as the sum of each components contribution to the heating value according to:

$$LHV_{syngas} = \frac{1}{100} \cdot \sum_i c_i \cdot LHV_i, \quad (1)$$

where the components i were H_2 , CO , CH_4 , C_2H_4 and C_2H_2 .

The Cold Gas Efficiency (CGE) was defined as the ratio between the energy in the produced cooled syngas and the energy input from the corresponding fuel according to:

$$CGE = \frac{\dot{m}_{syngas} \cdot LHV_{syngas}}{\dot{m}_{fuel} \cdot LHV_{fuel}}, \quad (2)$$

where the subscripted $\dot{m}$ represents the mass flow (kg/s) of fuel and syngas, respectively. LHV represents the lower heating value (MJ/kg) for fuel and syngas (subscripted), respectively. Two different Cold Gas Efficiencies (CGE's) were calculated for the process: CGE_{power} was based on LHV_{syngas} using all the combustible gas species in the calculation. CGE_{fuel} was based on LHV_{syngas} using only CO and H_2 concentrations in the calculation. The CGE_{power} is a representative measure for the gasification efficiency if the syngas is intended for power production, whereas CGE_{fuel} is considered as a better measure if the syngas is intended for synthetic fuel production, where CO and H_2 are the only important gas species.

Power consumption for fuel size reduction can be significant for entrained flow biomass gasification processes. The total plant efficiency, η_{plant} , taking the power consumption for milling into account, is of great importance for commercial applications. The electrical power used for milling can be generated in e.g. a gas turbine or gas engine from the syngas produced in the plant. However, the electrical efficiencies, η_{el} , for gas turbines or gas engines are currently approximately 0.3 – 0.4 [25]. In this work the plant efficiency, η_{plant} , was defined as:

$$\eta_{plant} = \frac{\dot{m}_{syngas} \cdot LHV_{syngas} - \frac{W_{milling}}{\eta_{el}} \cdot \dot{m}_{fuel}}{\dot{m}_{fuel} \cdot LHV_{fuel}}, \quad (3)$$

where the subscripted $\dot{m}$ and LHV represents the mass flow (kg/s) and LHV (MJ/kg) of fuel and syngas, respectively. The prime electrical power consumption for milling, W_{milling} (MJ/kg_{fuel}), is here compensated for the electrical efficiency, $\eta_{\text{el}} = 0.40$, of a gas turbine or a gas engine.

3 Results and discussion

3.1 Milling and fuel powders

The milling energy consumptions for the considered fuels are presented in Table 3. The Raw (un-torrefied) fuel required almost 36 kWh electricity per MWh_{th} of fuel (based on LHV), whereas the three torrefied fuels all required less than 10 kWh_{el}/MWh_{th}. The torrefied chips (Torr-300 and Torr-340) were brittle and required less force for breaking the chips perpendicular to the fiber direction compared to the Raw fuel. As mentioned earlier, the Torr-demo was delivered as pellets and therefore additionally pretreated compared to the other fuels. The pelletization process may explain why the Torr-demo fuel had the lowest milling energy.

In Figure 2, magnified pictures of the resulting powders are shown. The Raw fuel photo (A) show that the particles consist of elongated bundles of fibers. These particles are relatively large and there were also less fine particles in the Raw powder sample compared to the other three fuel samples. The fibrous particle structure can also be seen for Torr-300 (B) and Torr-demo (D). However, the most severely torrefied fuel, Torr-340 powder (C), had explicitly different particles compared to the other fuels. The fraction of fine particles was significantly larger than for the other fuels with essentially no large fiber bundles. This indicates that the particle size reduction efficiency increases with the degree of torrefaction.

3.2 *Gasification experiments*

3.2.1 *Temperature and operation performance*

The gasification experiments in this work were designed to fit within one working day for each fuel and the prepared amount of fuel powder was therefore limited by this restriction. The prepared fuel powders were either transported to hopper 1, hopper 2 or both for practical reasons or depending on the powder bulk density. In Figure 3 to Figure 6 the measured dry and N₂ free syngas compositions (mol% CO, H₂, CO₂ and CH₄) are presented together with the process temperature profiles for the four different gasification experiments. The average process temperature given by the three thermocouples at different azimuthal position at mid height in the reactor is hereafter referred to unless specified otherwise. All sharp temperature drops in the graphs are due to the cooling effect of the N₂ purge whenever the process was shut down. The Torr-300 fuel was the most voluminous fuel powder, Table 3. Therefore, it had to be filled in both hoppers in order to hold the required amount of fuel for the experiment. The gasification experiment started with feeding from hopper 1 (Figure 4), which gave relatively smooth temperature and gas concentration profiles. However, after a minor process interruption, the process was restarted from hopper 2, which resulted in much more irregular temperature and gas concentration profiles because of the unsteady fuel feeding from this hopper. Similar irregularities in the temperature profile can be noted for the Torr-demo experiment (Figure 6), which also was fed from hopper 2. However, even though there was an irregular fuel feeding, the variation of the syngas components CO, H₂ and CO₂ were within approximately ± 1 mol% in the Torr-demo case. The reason for the less consistent fuel feeding from hopper 2 is known and the plant was reconstructed after the experiments described in this work to avoid future problems.

3.2.2 Gasification process analysis

The accumulated runtimes and final process temperatures were different for the four experiments, i.e. none of the experiments reached thermal equilibrium, partly because the limited amount of fuel. In order to better compare the different fuels during these transient conditions, a temperature range of 1210°C – 1250°C was chosen for comparison. This temperature increase, 1210°C – 1250°C, required different amount of time for the different fuels. It took approximately 34 min, 44 min, 57 min and 78 min for Torr-340, Torr-300, Raw and Torr-demo, respectively. These differences in temperature increase rates may have several reasons. It may be explained by differences in flame structure and heat transfer processes during gasification. This needs, however, to be further investigated.

As expected, the syngas generated from the Raw fuel was relatively similar to the syngas from stem wood previously described by Weiland et al. [6]. In Table 4, the average main gas compositions (dry and N₂ free) for the temperature range 1210 – 1250°C are presented for the four fuels.

Compared to the results from gasifying the Raw fuel at the same temperature and equivalence ratio, the severity of torrefaction clearly affected the compositions of CO, CO₂ and CH₄, whereas there was no such obvious effect for H₂. However, the change in syngas composition may be an effect of the totally lower amount of available oxygen in the gasification process for the torrefied fuels as an artifact of the definition of the standard oxygen equivalence ratio (λ) used. From above, λ was defined as the ratio between the supplied O₂ and the O₂ addition at stoichiometric combustion. All experiments were run at the same oxygen equivalence ratio ($\lambda = 0.44$). As the total amount of oxygen available for reaction with C and H is highly influenced by the

oxygen content in the fuel, this variable will surely influence the gasification process chemistry if not compensated for.

If we define another variable, the Relative Oxygen Content (ROC), taking into account the whole oxygen content inside the gasifier, we create a fuel independent variable. The ROC was previously defined by Stemmler et al. [26] as:

$$ROC = \frac{O_2^{gasi} + O_2^{feed}}{O_2^{stoic}}, \quad (4)$$

where the superscripts are gasification (supplied O₂), feedstock and stoichiometric, respectively. Here the stoichiometric O₂ is defined as the total amount of O₂ available at stoichiometric combustion, i.e. both from the oxidant supply and from the feedstock.

As seen in Table 1, the oxygen content of the feedstock decreases with the degree of torrefaction. This implies that gasification experiments of the fuels in this work were performed at different ROC, and thus different stoichiometry, in the gasifier. Therefore, when gasifying fuels with different composition of C, H and O in the future, it would be beneficial to operate the gasification process at constant ROC instead of at constant λ .

Gasification of the Torr-340 fuel resulted in significantly lower CH₄ concentration, at any specific process temperature, compared to the other fuels in this work. Figure 7, in which the CH₄ concentrations are plotted against a common temperature axis illustrates this phenomenon. One possible explanation can be due to the fact that the torrefaction process removes lot of the volatile components of the biomass. The relationship between CH₄ release from pyrolysis and the biomass composition is however not clear in the existing literature. E.g. Couhert et al. [27] concluded that it was not possible to predict the pyrolysis gas yields, from an additivity law, from the biomass composition of cellulose, hemicellulose and lignin. Moreover, the pyrolysis yield of CH₄ showed no

1 correlation to the volatiles content of the tested biomasses. Nor showed the studies by
2 Couhert et al. [21], Chen et al. [22] or Qin et al. [28, 29] any relationship between the
3 biomass volatile content and the CH₄ yield from gasification. This was regardless
4 whether the volatile content was reduced by torrefaction or by comparing biomasses
5 with different initial volatile contents.

6 Higher flame temperature, in which CH₄ decomposes thermally, or longer residence
7 time in the gasifier are other possible explanations to the reduced CH₄ yield for the
8 Torr-340 fuel. The cause of this behavior is still unclear and needs to be investigated
9 further.

10 Table 4 presents the gasification performance figures for the temperature range 1210 –
11 1250°C. The two mildest torrefied fuels, Torr-300 and Torr-demo, resulted in the
12 highest carbon conversion and CGE figures; whereas the carbon conversion and CGE
13 were lower for the Raw and Torr-340 fuels. This is in accordance with the results
14 obtained by Chen et al.[22], who found an optimum in CGE at intermediate torrefaction
15 temperature. However, it should be noted that there was a problem with air leakage into
16 the gas sampling system for the Torr-300 experiment, which may have increased
17 experimental error of that experiment. The carbon conversion for the Torr-300
18 experiment was over predicted, probably as an effect of the gas sampling problem.

19 The carbon conversion is dependent on several different factors such as: the fuel particle
20 size distribution, the reactivity of the burning fuel particles, ROC, process temperature
21 and char reactivity. Despite the smallest fuel particle size distribution, the Torr-340 fuel
22 resulted in the lowest carbon conversion. From the experiments in this work it is not
23 possible to state whether it is because of a changed reactivity of the severely torrefied

fuel or if it is an effect of reduced ROC in the gasifier compared to the other experiments.

An interesting parameter to study is the plant efficiency, η_{plant} , which was significantly affected by the torrefaction pretreatment. The η_{plant} can be interpreted as the ratio between available energy in the cooled syngas and the thermal energy in the corresponding fuel, after taking the power consumption for milling into account. This means that η_{plant} equals $\text{CGE}_{\text{power}}$ if there was no power consumption for milling. The torrefied fuels resulted in η_{plant} approximately 0.01 – 0.02 units below the corresponding $\text{CGE}_{\text{power}}$, whereas the η_{plant} for the Raw fuel was significantly lower (0.09 units) than the corresponding $\text{CGE}_{\text{power}}$ due to a high power consumption for milling. However, the yield and efficiency of the torrefaction process itself was not considered in the present reasoning and the cost of torrefied fuels may potentially be higher than dried fuels for large scale applications. Thus, the benefit of low power consumption for milling may be canceled by a higher price of the torrefied fuels.

4 General conclusions

- The carbon conversion efficiency from gasification was enhanced by an intermediate torrefaction pretreatment, whereas both less- and more severe torrefaction resulted in reduced carbon conversions.
- The CH_4 yield was significantly reduced for the most severely torrefied fuel. The reason behind this behavior needs to be further investigated.
- On a general basis the torrefied fuels were feasible in terms of fuel handling/feeding and operation in the pressurized entrained flow gasification plant.

- The torrefaction pretreatment had a significant effect on power consumption for fuel size reduction, which was beneficial for the total plant efficiency.
- Using the Relative Oxygen Content (ROC) to define the gasification stoichiometry is advantageous when gasifying fuels with different composition of C, H and O. The ROC takes the whole oxygen content inside the gasifier into account and is therefore a fuel independent variable.

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5 Figure captions

Figure 1 Schematic process flow diagram for the PEBG process.

Figure 2 Pictures taken from a Zeiss light microscope. The fuel materials were all milled using a sieve size of 0.75 mm in the hammer mill and these pictures show representative samples of the resulting powders after milling. The powders are Raw (A), Torr-300 (B), Torr-340 (C) and Torr-demo (D).

Figure 3 Process temperature profile (top pane) and main gas (dry, N₂ free) composition (bottom pane) for the Raw fuel material.

Figure 4 Process temperature profile (top pane) and main gas (dry, N₂ free) composition (bottom pane) for the Torr-300 fuel material.

Figure 5 Process temperature profile (top pane) and main gas (dry, N₂ free) composition (bottom pane) for the Torr-340 fuel material.

Figure 6 Process temperature profile (top pane) and main gas (dry, N₂ free) composition (bottom pane) for the Torr-demo fuel material.

Figure 7 Measured CH₄ concentration in the syngas (dry and N₂ free) as a function of measured process temperature (average middle reactor temperatures).

6 Tables

Table 1. Chemical composition of raw and torrefied fuels.

Composition	Unit	Gasification feeds			
		Raw ^a	Torr-300	Torr-340	Torr-demo
Birch	%	45	45	45	0
Pine	%	55	35	35	50
Spruce	%	0	20	20	50
Torrefaction settings					
Time	min	--	4.5	4.5	45-60
Temperature	°C	--	300	340	245
Torrefaction results					
$\eta_{m,daf}$	%	100	80.2	49.2	$\sim 78^b$
$\eta_{E,HHV,daf}$	%	100	86.3	65.1	80.5
Fuel analysis					
Moisture content ^c	%	3.0	2.4	3.1	2.2
LHV	MJ/kg _{DS}	19.15	20.57	25.06	20.09
HHV _{daf}	MJ/kg _{daf}	20.69	22.02	26.53	21.49
Ash	% _{mass,DS}	0.9	0.7	1.2	0.5
Volatiles	% _{mass,DS}	82.5	78.3	56.8	76.7
Fixed carbon	% _{mass,DS}	16.6	21.0	42.0	22.8
C	% _{mass,DS}	50.9	54.4	65.4	53.1
H	% _{mass,DS}	6.2	6.0	5.3	5.9
N	% _{mass,DS}	0.2	0.2	0.3	0.1
O	% _{mass,DS}	41.8	38.7	27.8	40.4
S	% _{mass,DS}	0.02	<0.01	<0.01	<0.01
Cl	% _{mass,DS}	<0.01	<0.01	<0.01	<0.02

^a Similar, but not exactly the same as the original biomass for the Torr-300 and Torr-340 fuels.

^b Approximated value

^c Moisture content of feed prior to gasification (pulverized fuels)

1 **Table 2 Gasification settings**

Parameter	Unit	Raw	Torr-300	Torr-340	Torr-demo
Fuel feeding rate	kg/h	55	50	40	50
Thermal power	kW _{th}	284	265	258	271
O ₂ flow rate	kg/h	34	34	33	32
N ₂ flow rate	kg/h	11	11	10	10
Oxygen equivalence ratio (λ)	-	0.44	0.44	0.44	0.44
Relative Oxygen Content (ROC)	-	0.58	0.56	0.52	0.57
System pressure	bar(a)	2.0	2.0	2.0	2.0
Quench water level ^d	%	30	33	33	30

2 ^d Bubbling quench if the water level > 20 %.

3

1 **Table 3 Milling energy consumption and resulting fuel powder bulk density for the considered fuel materials.**

Parameter	Unit	Raw	Torr-300	Torr-340	Torr-demo
Milling energy	kWh _{el} /MWh _{th}	35.9 ± 0.7	8.1 ± 2.0	6.1 ± 0.7	4.6 ± 0.3
Fuel powder bulk density	kg/m ³	279	213	262	486

2

1 **Table 4 Gasification results measured within process temperature range 1210-1250°C. Gas compositions as**
2 **average dry and N₂ free.**

	Unit	Raw	Torr-300	Torr-340	Torr-demo
CO	mol%	50.0	54.6	60.3	54.0
H ₂	mol%	26.2	27.2	26.7	28.0
CO ₂	mol%	23.3	18.6	12.7	16.9
CH ₄	mol%	1.8	1.6	0.9	1.8
H ₂ /CO	-	0.52	0.50	0.44	0.52
Carbon conversion	-	0.89	1.10	0.84	0.97
LHV _{power}	MJ/kg ^e	7.2	8.1	8.3	8.3
LHV _{fuel}	MJ/kg ^e	6.6	7.6	8.0	7.7
CGE _{power}	-	0.58	0.81	0.63	0.70
CGE _{fuel}	-	0.54	0.76	0.61	0.65
Plant efficiency, η_{plant}	-	0.49	0.79	0.62	0.69

3 ^e kg dry gas

4

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7